Apparatus and method for low-temperature training of shape memory alloys

A M Swanger[1], J E Fesmire[2], S Trigwell[3], T L Gibson[4], M K Williams[5] and O Benafan[6]

[1] NASA Kennedy Space Center, Cryogenics Test Laboratory, NE-M5, KSC, FL 32899 USA
[2] NASA Kennedy Space Center, Cryogenics Test Laboratory, UB-R1, KSC, FL 32899 USA
[3] Sierra Lobo ESC, Kennedy Space Center, ESC-850, KSC, FL 32899 USA
[4] Vencore ESC, Kennedy Space Center, ESC-872, KSC, FL 32899 USA
[5] NASA Kennedy Space Center, Exploration Research & Technology, UB-R3, KSC, FL 32899 USA
[6] NASA Glenn Research Center, Cleveland, OH 44135 USA

Abstract. An apparatus and method for the low-temperature thermo-mechanical training of shape memory alloys (SMA) has been developed. The experimental SMA materials are being evaluated as prototypes for applicability in novel thermal management systems for future cryogenic applications. Alloys providing two-way actuation at cryogenic temperatures are the chief target. The mechanical training regimen was focused on the controlled movement of rectangular strips, with S-bend configurations, at temperatures as low as 30 K. The custom holding fixture included temperature sensors and a low heat-leak linear actuator with a magnetic coupling. The fixture was mounted to a Gifford-McMahon cryocooler providing up to 25 W of cooling power at 20 K and housed within a custom vacuum chamber. Operations included both training cycles and verification of shape memory movement. The system design and operation are discussed. Results of the training for select prototype alloys are presented.

1. Introduction

Thermal management for space launch systems, hardware, spacecraft, and habitats entails the need to move heat from one region to another for energy supply or to manage the transmission of heat to protect a given component, habitat surface, or person. At NASA Kennedy Space Center (KSC) and NASA Glenn Research Center (GRC) research work is being conducted to combine novel SMA material systems with novel approaches for the management of heat flow in the range of 4 K to 400 K (cryogenic to moderate temperatures). Although research into potential applications of low temperature shape memory alloy (SMA) materials has been explored, the science and understanding of SMA phenomena in the cryogenic realm is still in its infancy [1-4]. Envisioned are new systems incorporating SMA materials and a plurality of moving elements that can respond to certain temperatures to transmit the desired heat flux between two broad area surfaces. The broad area surfaces could be cryogenic tanks, habitat walls, space radiators, or any number of different systems, and be comprised of metals, composites, or hybrid materials.

In the design and development of these prototype adaptive thermal management systems there exists the need for thermo-mechanical training (or shape training) at very low temperatures. A custom Apparatus for Low-Temperature Training of Materials (ALTM) was devised, designed, and built to support this effort, as well as other applied research in low-temperature thermal management systems. Figure 1 shows the low-temperature material training apparatus in operation at the KSC Cryogenics Test Laboratory (CTL).

Figure 1. Apparatus for Low-Temperature Training of Materials (ALTM): actuator and upper feed-through (left); overall view with cryocooler in background, and data acquisition in foreground (right).

Novel features of the training apparatus include: the capability to remove and replace different specimens; video camera feed; and a temperature range from ambient down to near 20 K (liquid hydrogen temperature) using a cryocooler. A miniature video camera was adapted for use inside the vacuum chamber to understand the movement of the material test specimen in response to the temperature condition imposed by the cryocooler. The live video feed also provides clear insight on the movement of the actuator assembly within the apparatus.

The SMA materials used were experimental alloys being developed by GRC and evaluated for incorporation into novel designs for adaptive, multifunctional thermal management systems in future cryogenic applications; alloys providing two-way actuation at cryogenic temperatures were the chief targets. The mechanical training regimen for these low-temperature SMA materials was focused on the controlled movement of rectangular strips, with S-bend configurations, at temperatures around 30 K. Operations included both training cycles and verification of shape memory movement.

2. Shape memory alloy test specimens

The term “Shape Memory Alloy” or SMA refers to a group of materials that demonstrate an ability to return to some previously defined shape when subjected to the appropriate thermal procedure. Typically, these materials can be plastically deformed at some relative lower temperature, and then, upon exposure to some higher temperature, will return to their original, pre-deformed shape— materials that exhibit this property are referred to as one-way shape memory. However, some materials also undergo shape change upon re-cooling, hence, are referred to as two-way shape memory; these are the types studied during the effort presented here.

Generally, an alloy undergoes a transformation from the austenite phase to the martensitic phase in response to strain below the transformation temperature, which is then reversed upon heating, returning to the parent phase. A wide range of alloy materials exhibit the shape memory property, but the commercially available ones are only those that exhibit substantial amounts of strain recovery force upon shape change—although many of these alloys have been studied for two-way behavior and properties, only few have achieved varying degrees of success [3, 5, 6]. Additionally, the transformation

can exhibit hysteresis, in that the transformation on heating and cooling do not overlap. Small changes in the composition ratios can also have a significant effect on the transformation temperature. All of these factors make the study and utilization of SMA materials a challenge and demand liberal use of trial-and-error to make progress. This challenge is especially true of alloys possessing extremely low (i.e. cryogenic) transition temperatures, as the training regimens required demand a considerate level of effort to produce and operate at such temperatures.

The focus of the current work is the thermo-mechanical training of rectangular, S-shaped SMA specimens considered to exhibit two-way behavior at low temperatures for use in a prototype design for demonstrating adaptive thermal behavior. The test specimens measure approximately 40 mm long by 10 mm wide by 1 mm thick with an out-of-plane S-bend of 10 mm. Figure 2 shows a typical SMA test specimen used during two-way training with the ALTM.

Figure 2. Typical S-shaped SMA specimen

3. Training apparatus requirements and design

Treatment and shape training of SMA's has been done extensively at ambient to elevated temperatures; however, few efforts have addressed these methods at low temperatures (i.e. cryogenic) [3, 6, 7]. With the transformation temperatures of some specimen alloys used during testing thought to be below that of liquid nitrogen (77 K)—and use of a cryogen with a lower boiling point such as helium, hydrogen or neon was deemed either too dangerous or impractical—training options were limited. The solution came in the form of a commercial Gifford-McMahon cryocooler system that was already available at the CTL.

This unit is a Cryomech AL230 model capable of 25 W of refrigeration power at 20 K. The cold-head dimensions are 340 mm in length with a copper heat head diameter of 83 mm. A custom vacuum enclosure with a single 40 mm KF-style vacuum port at the closed end (visible in figure 1) was integrated with the cryocooler to provide the working environment necessary to reach extremely low temperatures.

Procedurally, the specimens needed to be subjected to high temperature annealing in the S-shape, followed by numerous rounds of cool-down, plastic deformation via compression until flat, and then controlled warm-up unloaded in order to achieve two-way actuation in the desired direction. Figure 3 illustrates this process in three stages.

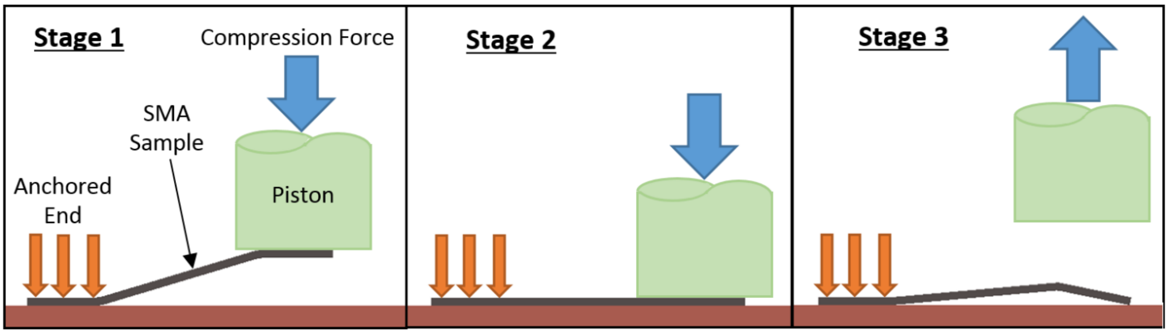

Figure 3. Simplified SMA training sequence. Stage 1: SMA and piston have thermalized and compression commences; Stage 2: specimen is compressed until flat; Stage 3: specimen is unloaded,

piston is drawn a distance away, and the SMA starts to return to its original shape during warm-up back to ambient temperature.

With only 25 W of refrigeration power available, a very low heat-leak design was required to maintain the SMA test specimens at the cryogenic training temperatures. This requirement was also a challenge as a substantial piston was necessary to impart the force needed to completely flatten the specimens. The piston represents the potential for a large conductive heat leak from the ambient vacuum chamber to the specimen. Also, components coming into contact during compression—namely the SMA specimen and the piston face—needed to be as close to thermal equilibrium as possible to avoid unwanted specimen heat loads.

Another important design driver was that a single 40-mm port was the only way to connect to the vacuum pumping system, piston actuator, and pressure transducers; as well as the only path of entry into the vacuum chamber for the piston and thermocouple wires.

The design solutions were to use a six-way vacuum fitting to provide more access points at the chamber interface, and to construct the piston in three pieces. A low-conductivity G10 cylinder (tube)—that transfers force to the specimen and provides a path for chamber evacuation and instrumentation lead wires through carefully placed radial holes—bolted to an aluminum cold-head, employing a press-fit G10 face that contacted the specimen during compression. One end of the G10 cylinder was magnetically coupled to, and actuated by, a 40 mm vacuum valve outside the chamber (roughly 0.5 m away from the cryocooler cold-head). Coupling was necessary to draw the piston from SMA specimen prior to warm-up; magnets were employed to ease operation and assembly of the system. At the bottom end an aluminum piston head acted to maintain axial piston position (via a slip-fit into a machined guide), and provided a cold thermal anchor for the G10 face. This piston head was machined from a piece of 6061 aluminum hexagonal bar stock to provide flat surfaces for attach points in case thermal straps were found to be necessary.

Composite G10 was used for the piston face instead of aluminum for two reasons: 1) lower thermal conductivity for greater thermal stability when compression was initiated and 2) removability so thermocouples could be directly embedded and the entire plug pressed in using a shop vise. Figure 4 shows a 3-D rendered model of the piston assembly and the aluminum piston head with G10 face and embedded thermocouples.

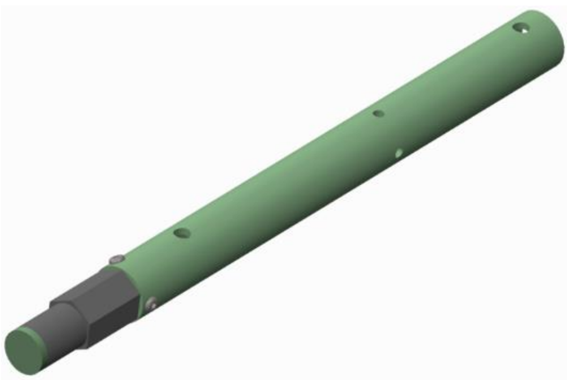

Figure 4. Compression piston assembly (left); and piston head, G10 face, and embedded thermocouples (right).

To house the SMA specimen and guide the piston, a test specimen holing fixture assembly was designed that integrated with the cryocooler cold head. This unit had to securely fix one end of the S-shaped specimen in order to provide good thermal contact for cool-down, and act as an anchor point during compression. The assembly was comprised of four main components: a copper foundation block directly affixed to the cryocooler cold-head, a cylindrical aluminum piston guide, a brass SMA fixture block, and a stainless steel bearing block.

The guide was bored-out to accommodate the aluminum piston head shown in Figure 5 with a slip-fit tolerance. This design feature allowed for full piston travel during compression (roughly 10 mm), while maintaining an accurate axial position. The fit between the two components was tight enough to promote reasonable heat transfer yet not so tight as to cause binding. Additional tolerances were also given to account for the slight imperfections in axial alignment between the vacuum chamber port and the fixture assembly. At the base of the guide a square notch was machined out to allow the free end of the SMA specimen to protrude into the cylinder; positioning it directly underneath the piston face.

Anchoring the other end of the specimen was achieved by sandwiching it between a square brass bar with an accurately sized relief cut into the bottom, and the copper foundation block. This fixture block was then secured to the copper via an 8-32 threaded rod and nut. This configuration afforded good thermal contact between the copper cold-mass and the specimen, and provided a strong anchor-point during compression.

Due to the shape of the specimen it was realized that during compression the bottom edge of the free end would be first to contact the flat, copper foundation block. Because the SMA material was much harder than copper, a stainless steel bearing block was employed at the interface to prevent gouging. Figure 5 shows the test specimen holding fixture and compression piston assembly integrated with the cryocooler cold head.

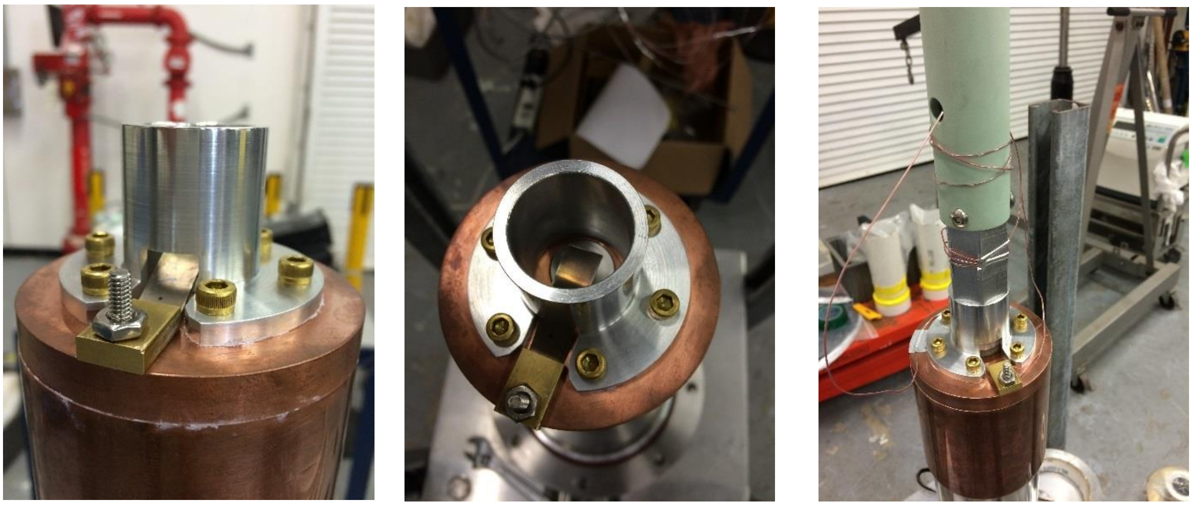

Figure 5. Test specimen holding fixture assembly integrated with the cryocooler (left and middle); compression piston mounted to holding fixture (right).

In this configuration, the solid conduction heat leak through the piston was calculated to be 130 mW (between 300 K and 20 K). Considering solid conduction to be the dominate source of heat leak—since the other cold components would be super-insulated and in high vacuum—the estimated demand for less than 0.1% of the total available refrigeration power effectively satisfied the design requirement.

4. Training apparatus set-up and operation

Untrained, flat SMA specimens were first placed a stainless steel training jig that bent them to the correct S-shape. They were then annealed in an oven at 450 °C for one hour, and immediately quenched in a water bath. A single test specimen was then positioned in the training fixture followed by mounting of the compression piston assembly. Six type-E thermocouples were strategically placed within the system: one each on the cryocooler cold head and aluminum piston guide and redundant pairs on the specimen itself and G10 piston face. These wires fed through the middle of the G10 piston cylinder inside the vacuum chamber volume via radial holes, ran up through the 40 mm port, back out through holes drilled higher up on the cylinder, and eventually interfaced at two thermocouple feed-throughs (visible in figure 1). Figure 6 shows a system cut-away of the overall hardware configuration.

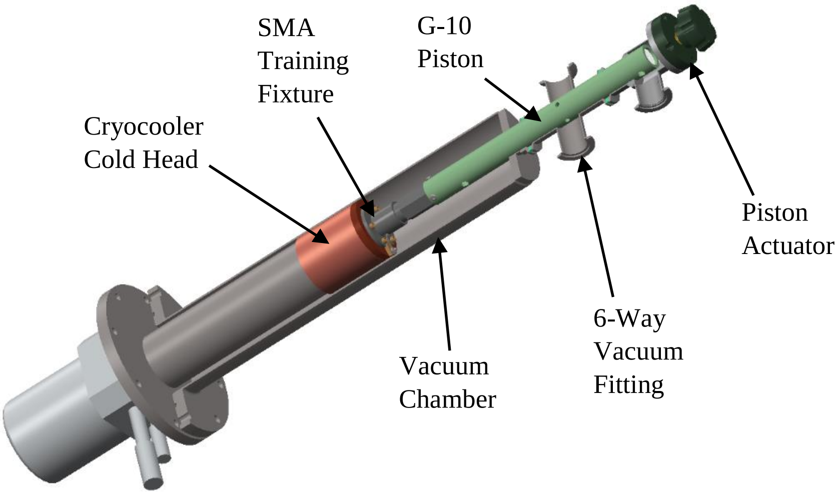

Figure 6. Cut-away of ALTM hardware configuration.

With the test specimen and instrumentation in place the cold head, holding fixture, and aluminum piston were wrapped with 20 layers of Cryolam multi-layer insulation (MLI). The vacuum chamber is then carefully slid down over the G10 cylinder. Thermocouples are interfaced to their respective feed-throughs at the 6-way vacuum cross, along with two Baratron capacitance manometers (100 and 0.1 torr ranges), and a vacuum pumping system. Finally, the piston actuator (i.e. a 40-mm vacuum angle valve) was interfaced to the top of the assembly, and a sight glass was employed in order to verify piston movement (visible in figure 1). All instrumentation was fed into Lab View data acquisition software, and displayed/recorded on a laptop.

After a one to two hour vacuum pumping period, the cryocooler was turned on to begin system cool-down. The test specimen and piston face were allowed to thermalize for approximately two hours. Compression was then applied using the actuator until the SMA specimen was pressed completely flat. The specimen was held in this position for one hour, after which time the piston was raised and the system was allowed to warm to room temperature under vacuum. This process was repeated four additional times, producing a total of five training cycles per SMA specimen. Figure 7 shows a typical temperature plot for an SMA training cycle with the ALTM.

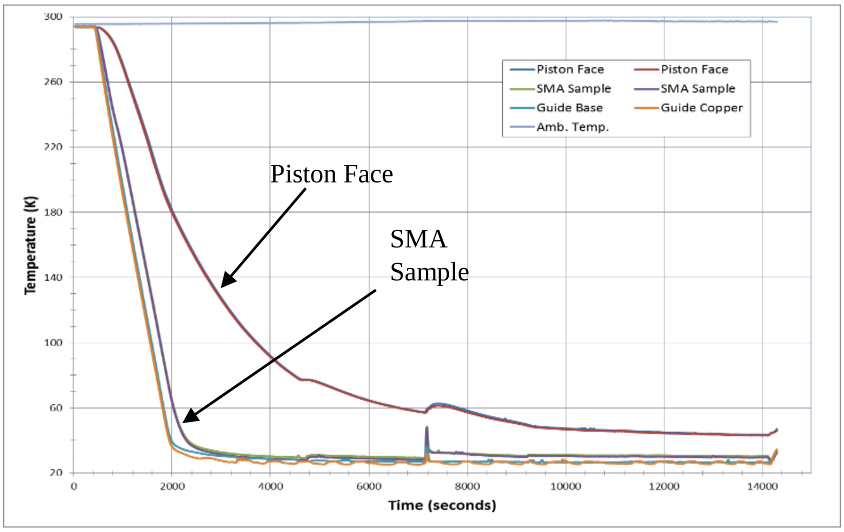

Figure 7. Example plot of temperature versus time for one training cycle of an SMA test specimen. (Note, the spike seen at ≈7200s is due to initiation of SMA sample compression)

5. Verification of two-way SMA actuation

After the SMA specimens had been subjected to the prescribed training regimen it was necessary to determine if cryogenic two-way actuation had been achieved. Numerous methods were explored in an attempt to accomplish this important but difficult task. Ultimately, the most successful and definitive method was to visually verify movement using a small camera routed through the vacuum chamber. This visual method was done using an inexpensive USB-style camera with integrated lighting. The head of the camera (10-mm diameter by measured 51-mm length) had four white LEDs whose brightness could be varied at the USB plug. To penetrate the vacuum chamber the cord was cut and each of the five wires fitted with female, barrel-style pins; these pins then interfaced with an 8-pin, 25 mm KF-style vacuum feed-through. Due to space constraints, the camera had to be mounted vertically inside the chamber, and aimed downward at a 45° mirror in order to see the edge of the S-shaped specimen. This configuration proved highly successful, producing high-resolution videos of each specimen during cool-down down to 30 K, and verifying that two-way actuation was in fact achieved in some cases. Figure 8 shows the setup for visual verification as well as a before-and-after of an actuated SMA test specimen.

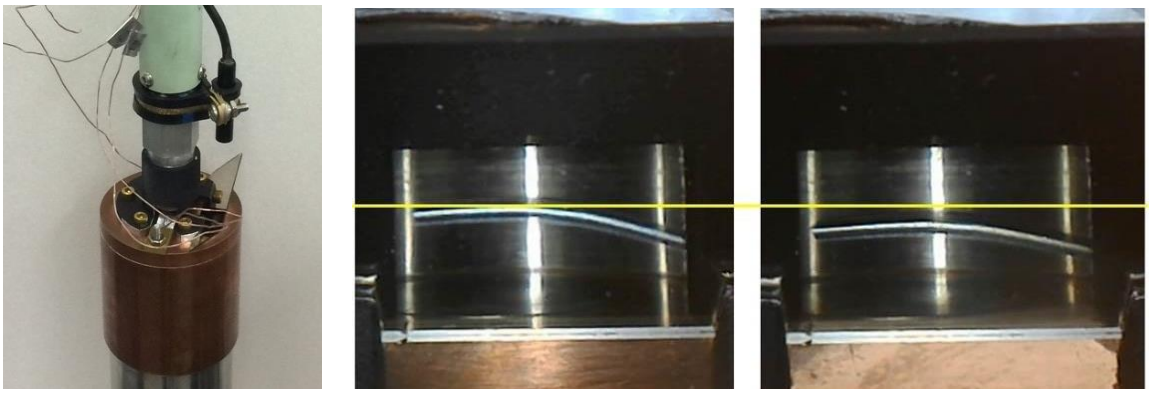

Figure 8. Visual verification setup showing USB camera and mirror (left); before-and-after screenshots showing SMA test specimen actuation (middle is warm, right is cold).

6. Conclusion

For the purposes of training shape memory alloys at cryogenic temperatures, the Apparatus for Low-Temperature Training of Materials (ALTM) was designed, built, and tested at the Cryogenics Test Laboratory of NASA Kennedy Space Center. Various S-shaped experimental SMAs were trained using the new apparatus at temperatures as low as 30 K, and resulted in successful two-way actuation in several cases. This result demonstrates the ALTM design and validates the developed thermo-mechanical training regimen for SMA prototype materials. A small video camera was also incorporated to provide verification of SMA actuation and proved to be extremely effective.

Major design challenges for the training apparatus included the need to keep heat-leak into the system to a minimum due to the limited refrigeration power available (25 W at 20 K); incorporation of a compression piston that could be actuated outside the vacuum chamber; and routing of all the required instrumentation and functional hardware through a single 40-mm vacuum port interface. These challenges were all successfully addressed resulting in an efficiently packaged, fully functional system that satisfied all the project goals as well as opening up new possibilities for materials research.

Research into the development, training and integration of low-temperature SMA materials shows great promise for many future applications in adaptive, multi-functional, and autonomous thermal management systems for in-space propulsion, cryogenic storage and transfer for ground and space systems, space habitation systems, and in-situ resource utilization. It is expected that along with the great possibilities come an infinite array of potential alloy compositions and inherent challenges as part of the development process. The motivation for the new ALTM was aimed at SMA training and proved very successful. It is fully expected that its capability will be extendable to a wide variety of other materials and situations where exercising material specimens at cryogenic temperatures is needed.

Acknowledgments
This work was funded by the NASA Space Technology Mission Directorate under Center Innovation Fund program and is part of the project *Low Temperature Two-Way Shape Memory Alloys for Thermal Management Systems*. Alloy development at GRC is supported by ARMD Advanced Air Transport Technology (AATT) and Transformational Tools & Technologies (TTT) Projects. Also, the authors would like to acknowledge Cryogenics Test Laboratory engineer Gino Carro, and technicians Johnny Kerce and Mark Velasco for their outstanding design, fabrication and testing support.

References
[1] Benafan O, Noebe R and Halsmer T, Low temperature shape memory alloys for adaptive autonomous systems *Power point presentation*, NASA Glen.
[2] Lemanski J 2005 Cryogenic shape memory alloy actuators for spaceport technologies: materials characterization and prototype testing *Master's Thesis*, University of Central Florida
[3] Malarria J, Lovey F and Sade M 2009 Two way shape memory effect in CuZnAl single crystals after pseudoelastic cycling at low temperatures *Materials Science and Engineering A* **517** 118-124.
[4] Abramov V Ya, Aleksandrova N M, Borovkov D V, Khmelevskaya I Yu, Korotitskiy A V, Makushev S Yu, Polyakova N A, Popov N N and Prokoshkin S D 2006 Martensitic transformations and functional properties of thermally and thermomechanically treated Ti-Ni-Nb based alloys *Materials Science and Engineering A* 438-440 553-557.
[5] Meng X, Chen F, Cai W, Wang L and Zhao L 2006 Two-way shape memory effect and its stability in a Ti-Ni-Nb wide hysteresis shape memory alloy *Materials Transactions* **47** 724-727
[6] Flores Zuniga H, Rios-Jara D, Belkahla S, Nika V and Guenin G 1996 The training and re-training procedures for the two way memory effect and its degradation in a Cu-Al-Be alloy *Scripta Materialia* **34** 1899-1904
[7] Lopez-Ferreno I, Breczewski T, Ruis-Larrea I, Lopez-Echarri A, No M L, and San Juan J 2013 Thermal treatments and transformation behavior of Cu-Al-Be shape memory alloys *Journal of Alloys and Compounds* **5775** S463-S467.